Ratcheting in Renewable Resources Contracting

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September 2004

Editor: Eva Roth

Department of Environmental and Business Economics
IME WORKING PAPER 58/04

ISSN 1399-3224

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Abstract

Real life implies that public procurement contracting of renewable resources results in repeated interaction between a principal and the agents. The present paper analyses ratchet effects in contracting of renewable resources and how the presence of a resource constraint alters the “standard” ratchet effect result. We use a linear reward scheme to influence the incentives of the agents. It is shown that for some renewable resources we might end up both with more or with less pooling in the first-period compared to a situation without a resource constraint. The reason is that the resource constraint implies a smaller performance dependent bonus, which reduces the first-period cost from concealing information but at the same time the resource constraint may also imply that second-period benefits from this concealment for the efficient agent are reduced. In situations with high likelihood of first-period pooling, the appropriateness of applying linear incentive schemes can be questioned.

Keywords: Political support function, political economy, environmental regulation, lobbyism, rent-seeking, taxation, auction, grandfathering, emission trading, European Union, interest groups, industry, consumers, environmentalists.

JEL Classification: Q28, H2, H4.

Acknowledgement: Thanks to Tommy Søndergaard Poulsen for valuable comments and to Pauline Madsen for editing the paper.

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1. Introduction

Contracting is common in renewable resource management. In Denmark, private forest owners franchise, for example, hunting to private explorers. In Canada, while the public owned forests are franchised to private users in Canada. For non-renewable resources a normal result in a static model in contract theory under private information is that the most efficient agent must be allowed the same level of effort as under full information. Jensen and Vestergaard (2002a) show that this result does not hold for a renewable resource in a static model. For a renewable resource the most efficient agent must be allowed a larger effort than under full information to fulfil the resource restriction.

In reality public procurement contracting has an inherently dynamic structure. The principal (a public agency) and the agents (the firms), between which contracts for the production of goods or services are made, often interact repeatedly. In this course of interaction, the principal might be able to extract vulnerable information about the characteristics of the agent, which makes it possible to re-design a contract so to increase the utility of the principal (i.e. social welfare). For example, if the agent initially has private information, the principal must accept a certain level of information rent if he faces an efficient agent in an adverse selection situation. However, over time the principal repeatedly observes the agents behaviour and may, thereby, be able to deduce something about the agents private information. This again may make it possible for the principal to revise contracts so as to capture some or all of the initial information rent. On the other hand, if the agent realizes this, he may adjust his behaviour so as to reduce the probability of the principal learning his private information. The agent will have an incentive to conceal his private information, and so the possibility of a pooling equilibrium exists. This effect is known as a ratchet effect.

The ratchet effect has been modelled by a number of researchers (see e.g. Freixas, Guesnerie and Tirole, 1985 for an early contribution)[1] using contracting setups with standard production technologies (i.e. public works, production of day care services, health care etc.). However, in some cases contracting situations involve exploitation of publicly owned renewable resources (like e.g. hunting or timber cutting in public forests, publicly owned ground or surface water resources etc.). Renewable resource problems are inherently dynamic because extraction in one period affects the extraction in the following periods and because the growth in the stock in the next period is partly determined by the extraction in this period. Therefore, standard ratcheting results may not apply and it even seems that the correct understanding of the dynamics of contracting under asymmetric information could be especially important for optimal design contract in renewable resource settings. Though much effort has been devoted to analysing optimal extraction paths over time for renewable resources (see e.g. the studies of optimal forests and ground water exploitation paths by Hanley *et al*., 1997 and Field, 2000 respectively) and renewable resource contracting has been studied (see e.g. Jensen and Vestergaard, 2002a) the implications of ratcheting have, to our knowledge, not been studied in a renewable resource context before.

The aim of this paper is to analyse the implications of the ratchet effect for public renewable resources contracting.[2] This is done in a model of a publicly owned renewable resource where exploitation is subcontracted to a private firm (the agent) that has private information about its own exploitation costs. The principal (the public authority) use a linear reward scheme. The model considers two periods where the principal can revise a reward scheme between the first- and second-period to affect harvest paths on the basis of the observed re-

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1 Other studies include Zou (1989), Richardson (1989), Dillén and Lundholm (1996) and Ortmann and Squire (2000).

2 In order to verify that short-term contracts are relevant for renewable resources we can imagine a principal that sets a total limit for harvest from a forest for a year. This total harvest can be allocated to agents as harvest within short-time periods (rations). The ration distributed to an agent can be changed during the year due to random variations in the stock of trees. Thus, contracts are relevant for managing renewable resources.

sult in the first-period. Our model is an extension of the original analysis by Freixas, Guesnerie and Tirole (1985) who show that a ratchet effect for a standard production technology implies that the principal should be more “generous” in a dynamic context in order to obtain information. We analyse two types of renewable resources. For some resources, costs are independent of the stock of the resource (for example timber cutting). The result from Freixas, Guesnerie and Tirole (1985) generalises to this case. For other resources costs depend on the stock of the resource (for example hunting and groundwater). The basic finding in this case is that the presence of a resource constraint might imply both more or less pooling in the first-period for some renewable resources, compared to a situation without a resource constraint. The reason for this result is that the resource constraint implies a smaller performance dependent bonus, which reduces the first-period cost from concealing information, but that the resource restriction may also reduce second-period benefits from this concealment for the efficient agent. The result that the likelihood of first-period pooling might be high is a serious problem for applying linear incentive schemes for renewable resources with stock-dependent costs.

Jensen and Vestergaard (2002a) analyse a fishery where the principal collects the revenue from the fishery while the agents (fishermen) bear the costs but receive a subsidy. However, the most commonly used contract within fisheries is individual quotas (IQs). With IQs the agents bear the costs and collect the revenue from extraction of the fisheries resource. However, timber cutting, hunting and groundwater are examples of renewable resources where public ownership occurs in many countries and, therefore, the analysis in Jensen and Vestergaard (2002a) is relevant for these renewable resources.

This paper is organized as follows. In the next section the general model is presented and the basis for the ratchet effect is analysed. Section 3 is devoted to a static analysis of the implications of using a linear incentive scheme for the regulation of renewable resources under asymmetric information, while section 4 expands the analysis to interaction in a dynamic context (ratchet effects). Section 5 concludes the paper.

2. Model and basic incentives

First we present the basic set-up for a renewable resource contracting situation very generally. This set-up constitutes the basis for the analysis in section 3 and 4. The renewable resource can cover any hunting situation and timber cutting. We assume a fixed price, *p*, on the harvest from the renewable resource and there are a number of agents indexed $i \in I = \{1,2,...,n\}$ who extract from the renewable resource.

Following Jensen and Vestergaard (2002a) we assume that the principal collects the revenue from harvesting the resource while extractors bear the costs. In order to secure exploitation of the resource the principal pays a linear subsidy to the agents given by $T_i(S_i) = a + bS_i$. The static profit function of agent *i,* which is equal to agents *i*'s objective function is, therefore, given by: $\pi_i(S_i, x) = a + bS_i - C_i(S_i, x)$, where S_i is agent *i*'s extraction, *x* is the stock of the renewable resource and C_i (S_i, x) is a cost function which depends on individual extractions and stock size.[3] Following Neher (1990), standard assumption on the cost function is made implying that $\frac{\partial C_i}{\partial x} \leq 0$, $\frac{\partial C_i}{\partial S_i} > 0$, $\frac{\partial^2 C_i}{\partial S_i^2} > 0$ and $\frac{\partial^2 C_i}{\partial x \partial S_i} > 0$, for all *i*, S_i and *x* (all the following assumptions are valid for all *i*, S_i and *x)*. The profit function implies that the agent maximises the profit in each period and disregards resource conservation measures. The implication of this is that each individual extractor disregards the effect that his harvest has on other extractors and, thereby, an externality arises (see Clark (1990)). This externality is often labelled the stock externality (see Anderson (1986)).

We assume that the agent is privately informed about a relevant parameter in the cost function. Basically, we assume a Bayesian environment, where all uncertainty is captured by a single parameter $\theta \in \{L, H\}$. θ is the type of an agent and $\theta = L$ denotes a low cost agent, while $\theta = H$ is a high cost agent. Formally, let $C_i(S_i, x, \theta)$ be the cost function with $C_i(S_i, x, L) < C_i(S_i, x, H)$. The realization of

3 The only restriction on S_i and x is that they are non-negative.

θ at the beginning of the principal-agent relationship is private information to each agent, while everything else is common knowledge. The principal has a common assessment of the likelihood of types, denoted as v for the probability of low cost type and (1-v) as the probability of high cost type. To get more structure on the types, we assume that $\frac{\partial C_i(S,x,H)}{\partial x} \geq \frac{\partial C_i(S,x,L)}{\partial x}$. Furthermore, it is assumed that the single crossing property is fulfilled implying that $\frac{\partial C_i(S_i,x,L)}{\partial S_i} < \frac{\partial C_i(S_i,x,H)}{\partial S_i}$. Define $S_i(\theta)$ as the extraction level of agent i, given the type is θ. In what follows it will be easier to assume, as done in most principal-agent relationships, that the principal faces one representative agent, which with probability v has low costs and with probability (1-v) has high costs. In this case, the expected (ex ante) extraction level is given by $S = n(vS_i(L) + (1-v)S_i(H))$.

Since we are analysing a renewable resource problem, we have to consider how it is renewed. Following standard assumptions in the renewable resource literature (see Conrad and Clark, 1987) define $F(x)$ as the natural growth rate. For renewable resources it is normally assumed that $F'(x) > 0$ for $x < x_{msy}$ and $F'(x) < 0$ for $x > x_{msy}$, where x_{msy} is the maximal sustainable yield. Furthermore, it is assumed that $F''(x) < 0$.[4] A resource restriction is now formulated (see Neher, 1990). This restriction implies that the change in stock sizes between time periods is equal to the natural growth rate minus the expected harvest. Following Jensen and Vestergaard (2002a) attention is restricted to steady-state equilibrium in this paper. Steady-state implies that the change in stock size between time periods is zero and, therefore, the resource restriction can be formulated as $F(x) = S$.[5]

4 See Conrad and Clark (1987) for an explanation of these assumptions.

5 A short discussion about how we interpret the intertemporal nature of regulation is useful. On the one hand, we assume that two periods exist, and at the same time we assume that in both periods, the renewable resource extraction is in a steady-state. If, i.e. in the first-period, information is fully revealed the regulation is changed, and the economy moves to another steady-state in the second-period. We do not model the adjustment to another steady-state, but for simplicity assume that the jump from one steady-state equilibrium to another happens instanta-

The principal wants to maximise the expected welfare from exploiting the resource. Following Jensen and Vestergaard (2002a) expected welfare is defined as the expected long-run economic yield from harvesting the renewable resource.[6] Let S_L and S_H denote the extraction of the agent when he has low and high cost, respectively.[7] The problem the principal faces has three types of constraints. First, all agents must be given incentives to participate (the participation constraints denoted PC^{θ}). Second, each type must be given incentives to choose the allocation designed for this type (the incentive compatibility constraints denoted IC^{θ}). Finally, the principal must keep the resource in a long run steady state equilibrium (the resource constraint denoted RC). The principal's problem is given by:

$$Max\ W = v(pS_l - C(S_L,x) - \lambda(a+bS_L)) + (1-v)(pS_H - C(S_H,x) - \lambda(a+bS_H))$$

$$s.t.$$

$$\pi(S_L,L) \geq \pi(S_H,L) \qquad (IC^L)$$

$$\pi(S_H,H) \geq \pi(S_L,H) \qquad (IC^H)$$

$$\pi(S_L,L) \geq 0 \qquad (PC^L)$$

$$\pi(S_H,H) \geq 0 \qquad (PC^H)$$

$$F(x) = S \qquad (RC)$$

where $\lambda > 0$ is the cost of public funds.[8]

neously. Note, however, that the results in the paper generalise to the case where adjustments towards steady-states are included. The only difference that arises when adjustments towards steady-state is possible is that the recommended regulation changes in every time period reflecting the adjustment paths towards a new steady-state equilibrium (see Sandal and Steinshamn, 1997). The assumption about steady-state is useful as the analysis is less complex with this assumption.

6 By maximising long-run economic yield discounting of future resource rents is excluded. Normally, future resource rents are discounted and the exploitation of the renewable resource is given a capital theoretical interpretation (see Clark and Munro, 1975). However, as in the case of steady-state, including discounting only means that the regulation changes over time. Therefore, attention is restricted to long-run economic yield to keep the model as simple as possible.

7 In this case type is indicated by subscript for the representative type.

8 See e.g. Laffont and Tirole (1993).

From the maximisation problem it is obtained that *F´(x) < 0* in optimum because the marginal stock costs are negative. Following Jensen and Vestergaard (2002b) RS can now be solved for *x* to yield $x = F^{-1}(x) = x(S)$ and because *F´(x) < 0, x´(S) < 0. x´(S)* can be interpreted as a biological response function and this function indicates how the steady-state stock responses to changes in aggregated catches. We can substitute $x = x(S)$ into the welfare function. Since we focus on the situation with only one representative agent it will be the case that $x = x(\nu S_L + (1-\nu)S_H)$. With respect to renewable resources we can distinguish between the cases summarised in Table 1.

Table 1: Various types of renewable resources compared to standard case

Standard case	$\frac{\partial C_i}{\partial x} = 0$	$\frac{\partial x}{\partial S} = 0$
Renewable resources with stock-independent costs (e.g., timber cutting)	$\frac{\partial C_i}{\partial x} = 0$	$\frac{\partial x}{\partial S} < 0$
Renewable resources with stock-dependent costs (e.g., hunting, groundwater)	$\frac{\partial C_i}{\partial x} < 0$	$\frac{\partial x}{\partial S} < 0$

In what follows a comparison between situations with and without resource restrictions is made. Given that the resource restriction is captured by *x = x(S)*, the case without a resource restriction corresponds to $\frac{\partial x}{\partial S} = 0.$ With respect to renewable resources, $\frac{\partial x}{\partial S} < 0$ because *F´(x) < 0* in optimum. However, for these resources two types exist. For some renewable resources the stock size does not influence the costs implying that $\frac{\partial C}{\partial x} = 0$. This would be the case for timber cutting (see Conrad and Clark, 1987). For other renewable resources $\frac{\partial C}{\partial x} < 0$ implying that the stock size influences costs. This would be the case for hunting and groundwater (see Field, 2000).[9]

3. Linear incentive scheme

Now the implications of a linear incentive scheme are analysed (first in a static environment and in the next section the two-period situation). A linear incentive scheme is, as mentioned in section 2, defined as $R(S_\theta) = a + bS_\theta$, where a is lump sum transfer and b is the performance dependent bonus. The profit for an agent of type θ given this reward scheme is by:

$$\pi_\theta = a + bS_\theta - C(S_\theta, x, \theta).$$

For notational ease, let the cost function be $C_\theta = C(S_\theta, x, \theta)$. The first order condition for profit maximization reads: $b = \frac{\partial C_\theta}{\partial S}$. Define $S_\theta = \arg\{b = \frac{\partial C_\theta}{\partial S_\theta}\}$. Given the assumption on the cost function, $S_L > S_H$. As mentioned in section 2, the welfare function in the static situation under full information, when the principal faces an agent of type θ, is given by:

$$W = \pi_\theta + p \cdot S_\theta - (1+\lambda)\cdot(a + bS_\theta) = p \cdot S_\theta - C(S_\theta, x, \theta) - \lambda(a + bS_\theta).$$

The PC restriction will be binding under full information and implies that IR $C(S_\theta, x, \theta) = a + b_\theta S_\theta$. Inserting this into the welfare function gives $W = p \cdot S_\theta - (1+\lambda)C(S_\theta, x, \theta)$. Maximizing with respect to b yields[10]

9 If fish was included in the analysis $\frac{\partial C}{\partial x} < 0$ would correspond to a search fishery while $\frac{\partial C}{\partial x} = 0$ corresponds to a schooling fishery (see Neher, 1990).

10 We use that $\frac{\partial C_\theta}{\partial b} = \frac{\partial C_\theta}{\partial S_\theta} \cdot \frac{\partial S_\theta}{\partial b} + \frac{\partial C_\theta}{\partial x} \cdot \frac{\partial x}{\partial S_\theta} \cdot \frac{\partial S_\theta}{\partial b}$ and $\frac{\partial x}{\partial S_H} = \frac{\partial x}{\partial S_L} = \frac{\partial x}{\partial S}$ and consider the general case, $\frac{\partial x}{\partial S} \neq 0$.

$\frac{\partial \mathrm{W}}{\partial \mathrm{b}} = p - (1+\lambda)\frac{\partial C_\theta}{\partial S_\theta} - \frac{\partial C_\theta}{\partial x}\cdot\frac{\partial x}{\partial S_\theta} = 0$. Inserting that $b = \frac{\partial C_\theta}{\partial S_\theta}$ yields $p = (1+\lambda)b + \frac{\partial C_\theta}{\partial x}\cdot\frac{\partial x}{\partial S_\theta}$. In case that $\frac{\partial x}{\partial S_\theta} = 0$ (the standard case) we have that $\frac{p}{1+\lambda} = b$,[11] while if $\frac{\partial x}{\partial S_\theta} \neq 0$ and $\frac{\partial C_\theta}{\partial x} \neq 0$ (renewable resources with stock-dependent costs) it will be the case that $b = \frac{p}{1+\lambda} p - \frac{\partial C_\theta}{\partial x}\cdot\frac{\partial x}{\partial S_\theta}$. Comparing the two cases we have that for stock-dependent costs (hunting and groundwater), *b* is lower, which implies that *S* is smaller as well. Reducing *S* increase the size of the stock and, thereby, the marginal costs of extraction are reduced.

In the case where the agent is privately informed about type, the expected welfare function reads:

$$\begin{aligned} W &= v[\pi_L - \lambda(a + bS_L)] + (1-v)[\pi_H - \lambda(a + bS_H)] = \\ &\quad v[(p-\lambda b)S_L - C_L] + (1-v)[(p-\lambda b)S_H - C_H] - \lambda a \end{aligned} \tag{1}$$

Maximizing of welfare implies that the PC constraint of the inefficient type is binding ($\pi_H = 0$ implying that $a = C_H - b_L S_H$).[12] To find *b*, insert this into equation (1):

$$W = v[(p-\lambda b)S_L - C_L] + (1-v)[(p-\lambda b)S_H - C_H] - \lambda[C_H - bS_H].$$

Maximizing with respect to *b* and using the fact that $b = \frac{\partial C_L}{\partial S} = \frac{\partial C_H}{\partial S}$ yields:

$$\begin{aligned} \frac{\partial \mathrm{W}}{\partial \mathrm{b}} &= v[(p-(1+\lambda)b - \frac{\partial C_L}{\partial x}\cdot\frac{\partial x}{\partial S})\frac{\partial S_L}{\partial b} - \lambda S_L] + (1-v)[(p-(1+\lambda)b - \frac{\partial C_H}{\partial x}\cdot\frac{\partial x}{\partial S})\cdot\frac{\partial S_H}{\partial b} - \lambda S_H] - \\ &\lambda[\frac{\partial C_H}{\partial x}\cdot\frac{\partial x}{\partial S}]\frac{\partial S_H}{\partial b} + \lambda S_H. \end{aligned}$$

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11 The standard result i.e. found in Freixas, Guesnerie and Tirole (1985).

12 This also is a standard result that in a pricipal agent relationship, in order to maximize welfare, the profit for the inefficient type must be squized to zero.

Setting $\frac{\partial \mathrm{W}}{\partial \mathrm{b}} = 0$ and rearranging gives:

$$[(p-(1+\lambda)b][v\frac{\partial S_L}{\partial b}+(1-v)\frac{\partial S_H}{\partial b}] = \lambda v[S_L - S_H] + \frac{\partial x}{\partial S}[v\frac{\partial C_L}{\partial x}\cdot\frac{\partial S_L}{\partial b}+(1-v+\lambda)\frac{\partial C_H}{\partial x}\cdot\frac{\partial S_H}{\partial b}] \quad (2)$$

Without a resource constraint, ($\frac{\partial x}{\partial S} = 0$) we have

$$[(p-(1+\lambda)b][v\frac{\partial S_L}{\partial b}+(1-v)\frac{\partial S_H}{\partial b}] = \lambda v[S_L - S_H].$$

In this case, $p-(1+\lambda)b > 0$. Under full information, we have that $b = p/(1+\lambda)$. However, under private information this relationship does no longer hold. The intuition is that by raising the bonus, *b*, above the (shadow) price of output, the efficient agents surplus (or information rent) is increased, which is socially undesirably. On the other hand, inclusion of the resource constraint for stock-dependent costs reduces *b* even further. Table 2 shows the value of *b* in the six cases.

Due to the first-order condition of the agent's optimization problem, $b = \frac{\partial C_L}{\partial S} = \frac{\partial C_H}{\partial S}$, and we have that $\frac{\partial S_\theta}{\partial b_\theta} > 0$. Therefore, it follows that when we take into consideration the private information and the resource stock in the case of stock-dependent costs, the extraction levels are reduced two-fold. First, due to the private information and the well known fact that in order to reduce the information rent the effort to the inefficient agent must be reduced. Second, because of the resource constraint for stock-dependent costs. Note that for stock-independent costs ($\frac{\partial C_i}{\partial x} = 0$ and $\frac{\partial x}{\partial S} < 0$), the reward is equal to the reward in the standard case. The reason for this is that when costs are independent of stock size, welfare and profit are unaffected by this variable and, therefore, the same *b* as in the non-resource case is obtained. However, for renewable resources with stock-dependent costs ($\frac{\partial C_i}{\partial x} < 0$ and $\frac{\partial x}{\partial S} < 0$), the performance dependent-bonus is lower because the stock size enters in the welfare and profit function.

Table 2: The performance-dependent bonus in the relevant cases

Resource	The value of the performance dependent bonus
Non-resources and full information	$b = \frac{p}{1+\lambda}$
Renewable resources with stock-independent costs and full information	$b = \frac{p}{1+\lambda}$
Renewable resources with stock-dependent costs and full information	$b = \frac{p}{1+\lambda} p - \frac{\partial C_\theta}{\partial x} \cdot \frac{\partial x}{\partial S_\theta}$
Non-resources and private information.	$b = \frac{p}{1+\lambda} - \frac{\lambda v[S_L - S_H]}{(1+\lambda)[v\frac{\partial S_L}{\partial b} + (1-v)\frac{\partial S_H}{\partial b}]}$
Renewable resources with stock-independent costs and private information	$b = \frac{p}{1+\lambda} - \frac{\lambda v[S_L - S_H]}{(1+\lambda)[v\frac{\partial S_L}{\partial b} + (1-v)\frac{\partial S_H}{\partial b}]}$
Renewable resources with stock-dependent costs and private information	$b = \frac{p}{1+\lambda} - \frac{\lambda v[S_L - S_H]}{(1+\lambda)[v\frac{\partial S_L}{\partial b} + (1-v)\frac{\partial S_H}{\partial b}]} - \frac{\frac{\partial x}{\partial S}[v\frac{\partial C_L}{\partial x} \cdot \frac{\partial S_L}{\partial b} + (1-v+\lambda)\frac{\partial C_H}{\partial x} \cdot \frac{\partial S_H}{\partial b}]}{(1+\lambda)[v\frac{\partial S_L}{\partial b} + (1-v)\frac{\partial S_H}{\partial b}]}$

The ratchet effect occurs due to the dependency between the belief the principal holds regarding type of agent in period one and the prospect of gaining intertemporal rent. In order to analyse this in our setting, it is necessary to find how the information rents depend on *b*. In the private information setting, the efficient type receives information rent. The reason is that the efficient type can always do better than the inefficient type. This combined with the participation constraint for the inefficient type, which implies that this type must be given non-negative profit, implies that the efficient type always gets a strict positive profit. At the extraction level for the inefficient agent, S_H, the information rent is determined as the profit that the efficient type receives by choosing S_H.[13] Therefore, the information rent is determined as follows. Inserting the binding *PC* for type *H* into the profit function of type *L*, $\pi_L = a + b \cdot S_H - C(S_H, x, L)$, yields $\pi_L(L) = C(S_H, x, H) - C(S_H, x, L)$. We are in particular interested in how the information rent changes, as *b* changes. The result is given in Lemma 1.

Lemma 1: $\frac{\partial \pi_L(L)}{\partial b} > 0$.

This follows from differentiation $\pi_L(L)$ with respect to *b*:

$$\frac{\partial \pi_L(L)}{\partial b} = \left(\frac{\partial C_H}{\partial S_H} \cdot \frac{\partial S_H}{\partial b} + \frac{\partial C_H}{\partial x} \cdot \frac{\partial x}{\partial S_H} \cdot \frac{\partial S_H}{\partial b}\right) - \left(\frac{\partial C_L}{\partial S_H} \cdot \frac{\partial S_H}{\partial b} + \frac{\partial C_L}{\partial x} \cdot \frac{\partial x}{\partial S_H} \cdot \frac{\partial S_H}{\partial b}\right) =$$
$$\left[\left(\frac{\partial C_H}{\partial S_H} - \frac{\partial C_L}{\partial S_H}\right) + \left(\frac{\partial C_H}{\partial x} - \frac{\partial C_L}{\partial x}\right) \cdot \frac{\partial x}{\partial S_H}\right] \cdot \frac{\partial S_H}{\partial b} > 0.$$

Due to the single crossing property, it follows that $\frac{\partial I(L)}{\partial b} > 0$. This holds for both stock-independent costs renewable resources ($\frac{\partial C}{\partial x} = 0$) and renewable resources with stock-dependent costs ($\frac{\partial C}{\partial x} < 0$). The value for $\frac{\partial \pi_L(L)}{\partial b}$ in the three cases is summarised in Table 3.

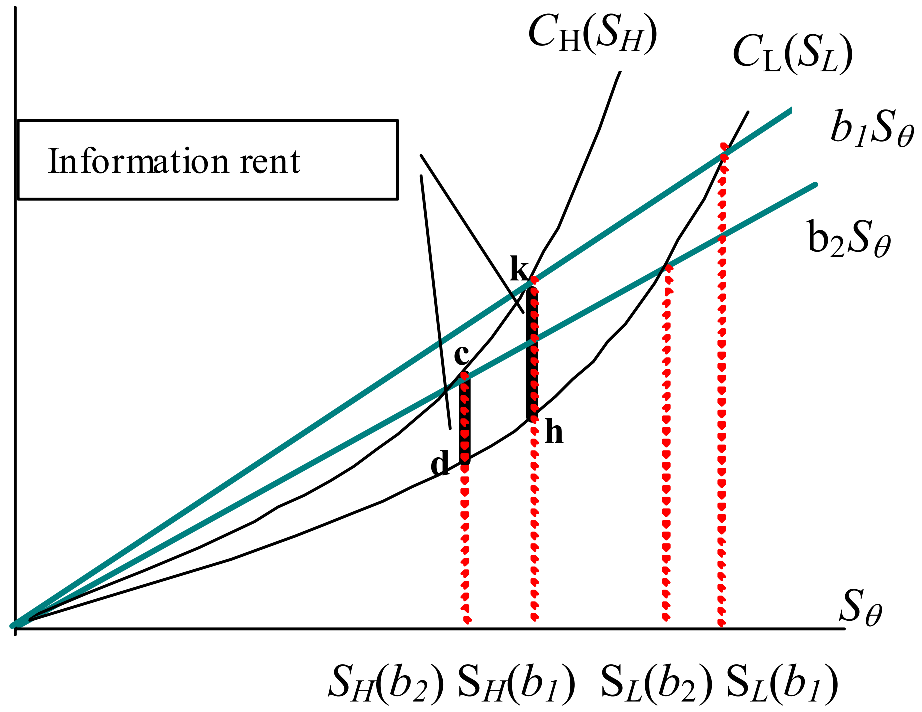
13 This follows from the fact that in optimum, the incentive compatibility constraint for the efficient will be binding.

Table 3: The value of $\frac{\partial \pi_L(L)}{\partial b}$

Type of resource	$\frac{\partial \pi_L(L)}{\partial b}$ is equal to
Standard case	$\frac{\partial C_H}{\partial S_H} - \frac{\partial C_L}{\partial S_L}$
Renewable resources with stock-independent costs	$\frac{\partial C_H}{\partial S_H} - \frac{\partial C_L}{\partial S_L}$
Renewable resources with stock-dependent costs	$[(\frac{\partial C_H}{\partial S_H} - \frac{\partial C_L}{\partial S_L}) + (\frac{\partial C_H}{\partial x} - \frac{\partial C_L}{\partial x}) \cdot \frac{\partial x}{\partial S_H}] \cdot \frac{\partial S_H}{\partial b}$

It is seen that the value of $\frac{\partial \pi_L(L)}{\partial b}$ is the same in the standard case and stock-independent costs. The reason for this result is that the stock size does not enter in the profit and welfare function if $\frac{\partial C}{\partial x} = 0$. For stock-dependent cost renewable resources the term $(\frac{\partial C_H}{\partial x} - \frac{\partial C_L}{\partial x}) \cdot \frac{\partial x}{\partial S_H}] \cdot \frac{\partial S_H}{\partial b}$ is added to $\frac{\partial \pi_L(L)}{\partial b}$. The main reason why under private information, *b* is lowered, is that the rent to the efficient type must be reduced. Since S_H is increased, $C_H - C_L(S_H)$ also increased due to the single crossing property. The results are illustrated in Figure 1.

Figure 1: The information rent to the efficient type



In Figure 1 the performance dependent bonus in the standard case (and stock-dependent costs) under private information is b_1. The low cost agent extracts $S_L(b_1)$, while the high stock agent extracts $S_H(b_1)$. The low cost agent receives an information rent of *kh*. For renewable resources with stock-dependent costs the bonus is b_2. $S_L(b_2)$ is the efficient agents harvest, $S_H(b_2)$ is the high cost agents harvest and cd is the information rent. S_L, S_H and the information rent are all lower for renewable resources with stock-dependent costs compared to non-resources (and renewable resources with stock-independent costs).

The result is not surprising, since in the general principal-agent model, the main reason to reduce the effort for the inefficient type is to reduce the information rent of the efficient type. The results of this section are summarized in the following proposition:

Proposition 1: A resource constraint for stock-dependent cost renewable resources (hunting and groundwater) implies (1) extractions are decreased for both types compared to the standard case and renewable resources with stock-independent costs (timber cutting) and (2) the efficient type receives *less* information rent compared to the standard and stock-independent costs cases.

The intuition of this proposition is as follow. The information rent is obtained since the low cost always can do better than the high cost type. In order to reduce the information rent, S_H is reduced. However, the inclusion of the resource constraint reduces S_H even further and so as a side effect also reduces the information rent to the efficient type. The main conclusion so far is that in a static situation, the information is less valuable for the efficient type.

Note that the result that extraction for renewable resources with stock-independent costs is reduced for both types is contrary to the result in Jensen and Vestergaard (2002a). In Jensen and Vestergaard (2002a) the extraction of the efficient type is increased. The differences in results arise because Jensen and Vestergaard (2002a) use a non-linear reward scheme, while a linear reward scheme is used in this paper. A non-linear reward scheme implies that more flexibility is allowed and, therefore, the extraction of the efficient type can be increased. However, the use of a non-linear incentive scheme may be questioned. A non-linear incentive scheme is from the point of view of practical contracting complex to use and because of this complexity the agents may misunderstand the scheme. Therefore, non-linear schemes are sometimes approximated with linear schemes (see Laffont and Tirole (1993)). Thus, it is natural to use a linear scheme in this paper.

4. Continuation equilibrium, linear incentive scheme

We now formulate a two-period version, $t=1$ and 2 where t is time, of the static model in section 3. In other words, a dynamic game between the principal and the representative agent is analysed. The agents now take into account how their actions in the first-period influence the inferences of the principal and, consequently, the prospect of gains in the second-period. One of the basic and important reasons for studying a ratchet effect is that the efficient type in a dynamic context might pool with an inefficient type.[14] The game has the following temporal structure. At the start of the first-period the principal chooses a scheme, (a_1,b_1), and a representative agent reacts to this scheme by extraction, S_1, at first-period cost $C_1(S_1,\theta)$. The agent is rewarded by $a_1+b_1S_1$, obtaining a first-period profit of $\pi_1(\theta)$. At the start of the second-period the principal chooses a new scheme (a_2,b_2) and the representative agent chooses a second-period extraction level, S_2, given second-period cost on $C_2(S_2,\theta)$. The agent is rewarded with $a_2+b_2S_2$ and obtains a second-period profit on $\pi_2(\theta)$. Welfare in period 1 and period 2 is denoted W_1 and W_2, respectively. Let $W=W_1+W_2$ and $\pi(\theta)=\pi_1(\theta)+\pi_2(\theta)$.

Perfect Bayesian equilibrium

The equilibrium concept applied in this paper is a perfect Bayesian equilibrium. The perfection criterion here assumes that for any first-period incentive scheme, and for any strategies chosen in the first-period, the second-period strategies are chosen optimally conditioned on first-period behaviour and based on Bayesian updating. This allows us to focus on first-period interactions as second-period actions are predetermined on the basis of first-period behaviour.

The set of players consists of nature, N, the principal and the representative agent. Let h_t denote the history of the game at the beginning of period t, i.e., the vector of actions up to period t. Allowing for mixed strategies, we let the strategies for the principal and the agent be a sequence of schemes, $\{(a_1(v_1),b_1(v_1)),(a_2(h_2),b_2(h_2))\}$, and extractions, $\{S_1(a_1,b_1,\theta),(S_2(h_2,a_2,b_2,\theta)\}$, respectively. The system of beliefs is denoted $\mu=(v_1,v_2(h_2))$ with $v_1=P(L)$ being a prior probability that the agent has low costs, and $v_2=P(L|\ h_2)$ is the posterior beliefs that costs are low defined as via Bayes rule.

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14 Note that subscripts in the dynamic settings indicate time periods.

As mentioned above we look for a perfect Bayesian equilibrium to this game, i.e., for a set of strategies, $\{(a_1,b_1)^*, S_1(b_1,\theta)^*, (a_2,b_2)^*, S_2^*\}$, and a system of beliefs satisfying:

P1 $\forall \theta \in \{L,H\}: S_2^* = \arg\max_{S_2} \pi^2$.

P2 Given $v_2(h_2)$ and $S_2^* : (a_2,b_2)^* = \arg\max_{\{a_2,b_2\}} \{v_2(h_2)W_2 + (1-v_2(h_2))W_2\}$

P3 Given $(a_2,b_2)^*$ and S_2^* and for all $\theta \in \{L,H\}: S_1(b_1,\theta)^* \in \arg\max_{S_1} \pi_1$

P4 Given $S_1(b_1,\theta)^*$, S_2^* and $(a_2,b_2)^* : (a_1,b_1)^* \in \arg\max_{\{a_1,b_1\}} W_1$

B $v_2(h_2)$ is Bayes-consistent with v_1 and the firms first-period strategy $S_1(\theta)$ and observed actions.

P1 implies profit maximization of the representative agent and states that for any history of the game, and any second-period incentive scheme, both types simply maximize their static profit. P2 requires that the principal offers an incentive system, $(a_2,b_2)^*$, that maximizes second-period welfare for any history of the play incorporated in the posterior beliefs, $v_2(h_2)$. P3 implies first-period profit maximization of the representative agent, now also taking into account the second-period incentive scheme and second-period harvest. P4 requires that the principal offers an incentive system, $(a_1,b_1)^*$, that maximizes first-period welfare taking into account the second-period incentive scheme and second-period harvest. Finally, B implies that updating of beliefs is consistent with Bayes rule (when possible).

The Perfect Bayesian equilibrium concept builds on a backward induction argument. Hence, the right framework is to consider the second-period first. For the second-period, we define a continuation equilibrium, which is a set of second-period strategies with an updating rule satisfying *P1*, *P2*, *P4* and *B* for an exogenous given first-period incentive scheme. For a given probability, $v_2(h_2)$, conditional upon the observed choice in the first-period of the representative agent, (h_2), the second-period incentive scheme is the optimal static incentive scheme for belief $v_2(h_2)$. The second-period incentive scheme yields no rent for the inefficient type and rent, $I(v_2)$, for the efficient type.

Let the scheme, (a_1,b_1), where a_1 is such that the PC constraint of both types is satisfied, be given. In any continuation equilibrium we must have the following structure:

(a) $S(a_1,b_1;H) = S(b_1,H)$
(b) $S(a_1,b_1;L) = \{S(b_1,L), S(b_1,H)\}$

(a) and (b) state that an inefficient type will choose its static optimal effort level, $S(b_1,H)$, while an efficient type will either also play its own static optimal effort level, $S(b_1,L)$, or else pool with the inefficient type at $S(b_1,H)$. No other strategies satisfy the above conditions.

Now it is clear that: (i) Whatever the principals beliefs, v_2, and, thereby, whatever action in the first-period for the efficient type, the principal will set a_2 such that the second-period profit for an efficient type is zero. It is, then, optimal for an efficient type to take the first-period action, $S(b_1,H)$. (ii) Given (i), if any other harvest than $S(b_1,H)$ is observed, the principal can perfectly infer that costs are low, and set a_2 such that second-period profits are zero. Hence, it is optimal for the low cost type to play its static maximizing level $S(b_1,L)$.

Define $\pi_t(v,\theta)$ as the profit for agent of type θ in period t, when the principal holds beliefs v that costs are low. One of the basic facts for a ratchet effect is summarised in lemma 2.

Lemma 2: $\pi_t(v,L)$ is continuously and decreasing in v.[15]

This means that an efficient agent's information rent is increasing in the belief that the agent is inefficient. The reason for this is that the principal most balance the costs of reducing harvest for the inefficient type and the saved information rent for the efficient type. The higher the belief that the agent is inefficient, the more weight is optimally put on the negative effect of reducing the

15 See e.g. Freixas, Guesnerie and Tirole (1985).

harvest of the inefficient agent, and, hence, optimal to accept more information rent.

Hence, given a two-period relationship, the principal might worry about an efficient type having strong incentive to pool with an inefficient type. In order to analyse this, we have to compare the cost from concealing information in period 1 for type L with the gain of concealment to this type. The cost for the efficient type in period 1 of concealing information, which is found when a low cost type chooses the harvest level that is optimal for a high cost type in a static situation, is:

$$\Delta(b_1) = b_1[S_H - S_L] - [C_L(S_H) - C_L(S_L)].$$

The term in the first bracket on the right hand side is the costs of foregone output in period 1 and the term in the second bracket is the saved cost of output.

It is important to evaluate how the cost of concealment is influenced by changes in b_1.

Lemma 3: $\frac{\partial[\Delta(b_1)]}{\partial b_1} > 0$ in the standard case and renewable resources with stock-independent costs. If $[S_L - S_H] > [\frac{\partial C_L}{\partial x}\frac{\partial x}{\partial S_L}(\frac{\partial S_H}{\partial b_1} - \frac{\partial S_L}{\partial b_1})]$, $\frac{\partial[\Delta(b_1)]}{\partial b_1} > 0$ also holds for stock-dependent cost renewable resources.

To prove lemma 3, we have that:

$$\frac{\partial \Delta(b_1)}{\partial b_1} = \left[S_L - S_H + b_1\frac{\partial S_L}{\partial b_1} - b_1\frac{\partial S_H}{\partial b_1}\right] - \left[\frac{\partial C_L}{\partial S_L}\frac{\partial S_L}{\partial b_1} + \frac{\partial C_L}{\partial x}\frac{\partial x}{\partial S_L}\frac{\partial S_L}{\partial b_1} - \frac{\partial C_L}{\partial S_H}\frac{\partial S_H}{\partial b_1} - \frac{\partial C_L}{\partial x}\frac{\partial x}{\partial S_H}\frac{\partial S_H}{\partial b_1}\right] =$$
$$[S_L - S_H] + [(b_1 - \frac{\partial C_L}{\partial S_L})\frac{\partial S_L}{\partial b_1} - (b_1 - \frac{\partial C_H}{\partial S_L})\frac{\partial S_H}{\partial b_1}] + [\frac{\partial C_L}{\partial x}\frac{\partial x}{\partial S_L}(\frac{\partial S_H}{\partial b_1} - \frac{\partial S_L}{\partial b_1})].$$

For all three cases, the first term is positive and the second term is zero because the expression in the bracket is the first order condition for the representative agent. In the standard case the third term is zero because $\frac{\partial x}{\partial S_L} = 0$ and for stock-independent cost renewable resources the third term is also zero because $\frac{\partial C_L}{\partial x} = 0$. Therefore, $\frac{\partial[\Delta(b_1)]}{\partial b_1} > 0$ for these two cases. With respect to stock-dependent costs, the third term is negative because $\frac{\partial x}{\partial S_L} < 0$ and $\frac{\partial C_L}{\partial x} < 0$. However, if $[S_L - S_H] > [\frac{\partial C_L}{\partial x}\frac{\partial x}{\partial S_L}(\frac{\partial S_H}{\partial b_1} - \frac{\partial S_L}{\partial b_1})]$, then $\frac{\partial[\Delta(b_1)]}{\partial b_1} > 0$. This seems reasonable because the marginal stock costs for, for example, groundwater, $\frac{\partial C_L}{\partial x}$, is low (see Field, 2000). Therefore, we proceed with the assumption that $\frac{\partial[\Delta(b_1)]}{\partial b_1} > 0$ for renewable resources with stock-dependent costs. The results are summarised in Table 4.

Table 4: The value of $\frac{\partial[\Delta(b_1)]}{\partial b_1}$

Type of resource	$\frac{\partial[\Delta(b_1)]}{\partial b_1}$ is equal to
Standard case	$[S_L - S_H]$
Renewable resources with stock-independent costs	$[S_L - S_H]$
Renewable resources with stock-dependent costs	$[S_L - S_H] + \left[\frac{\partial C_L}{\partial x}\frac{\partial x}{\partial S_L}(\frac{\partial S_H}{\partial b_1} - \frac{\partial S_L}{\partial b_1})\right]$

From Table 4 it is seen that $\frac{\partial[\Delta(b_1)]}{\partial b_1}$ is smaller for resources with stock-dependent costs than for stock-independent costs renewable resources. Renewable resources with stock-independent costs yield the same result as non-resources because stock size does not enter the welfare and profit functions for these resources.

Let the gain of concealment for the low cost type, which occurs in the second-period, be denoted $\pi_2(v, L)$. Given lemma 2, the smaller *v*, the higher the gain to an efficient type from concealing its type. Hence, the maximum second-period rent is $\pi_2(0, L)$. We now state the condition for separating, pooling and semi-separating continuation equilibria.[16]

Lemma 4: For any given b_1:[17]

1) There exists a unique pooling continuation equilibrium iff b_1 is such that

$$\Delta(b_1) \le \pi_2(v_1, L).$$

2) There exists a unique separating continuation equilibrium iff b_1 is such that

$$\Delta(b_1) \ge \pi_2(0, L).$$

3) There exists a unique semi-separating continuation equilibrium iff b_1 is such that

$$\pi_2(v_1, L) < \Delta(b_1) < \pi_2(0, L).$$

First look at 2). Here the cost of concealment is so high, that even in the case where the principal believes that costs are truly high (in which case the second-period gain is $\pi_2(0, L)$, and, hence, the benefits from concealment are maximized), it is not profitable for an efficient type to pool with the inefficient

16 We only need to verify the existence of these types of equilibrium, since what we are interested in is how these conditions change as *b* changes.

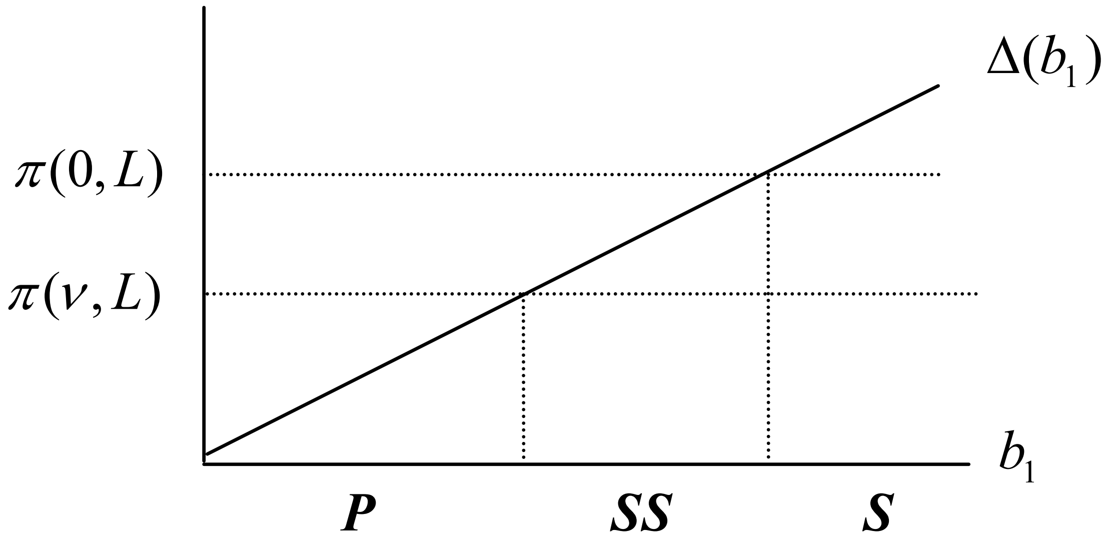
17 See Freixas, Guesnerie and Tirole (1985) for a proof of this. Note that *a*1 is such that the IR constraints of both types are satisfied.

type.[18] Next turn attention to 1). In a pooling equilibrium, no new information is revealed, and $v(h(b_1, L)) = v_1$. A pooling equilibrium exists when it is beneficial for the efficient type to pool even when prior beliefs remain unchanged. In 3) it is optimal for the efficient type to randomize between S_L and S_H since it is not beneficial for an efficient type to pool given unchanged type, but to do so if the regulator would believe costs were high as shown in figure 2.

We will now analyse the implications of the ratchet effect on the optimal structure of the incentive schemes in a fully dynamic context. So far we have shown the existence of a unique continuation equilibrium for a given first-period scheme and now we focus on a characterization of the optimal first-period reward scheme. A full characterization of the optimal first-period scheme in the case without resource constraint can be found in Freixas, Guesnerie and Tirole (1985). The intuition in this standard setting is that if the regulator in the intertemporal setting by choosing $b(v_1)$ (the optimal static incentive) the induced continuation equilibrium is separating, then $b(v_1)$ is also optimal in this dynamic setting. However, if $b(v_1)$ induces pooling, then it is optimal to raise b above $b(v_1)$, the reason is that pooling will always be at the inefficient type's harvest level, and increasing b will therefore increase the output of both, which is optimal.

18 Suppose the unique equilibrium is separating. From (a) and (b), page 15, it follows that the two types in period one play their optimal static strategies. This implies that $v_2((a_1, b_1), S(b_1, H)) = 0$ and $v_2((a_1, b_1), S(b_1, L)) = 1$. As this equilibrium is separating the gain of concealment $\delta\pi_2(0, L)$, cannot exceed the loss $\Delta(b_1)$. Conversely, suppose that (2) holds. For any out-of-equilibrium strategy $S_1 \notin \{S(b_1,L), S(b_1,H)\}$, choose again $v_2=1$. This together with the fact that (2) holds induces the low type to play $S_1=S(b_1,L)$.

Figure 2: Pooling, semi-separating and separating equilibria as a function of b_1[19]



In this paper we focus on the implications of including a resource constraint for both stock-dependent and stock-independent renewable resources. The focus of our analysis is whether the inclusion of the resource constraint alters the result that increasing b above $b(v_1)$ increases welfare. This is relevant because of the stock externality effect which implies that increasing b reduces the stock and hence increases the harvest.

Define b_1^D as the optimal dynamic first-period b, and let $b(v_1)$ be the static optimal b_1, given prior beliefs v_1. First, we derive a lower bound for b_1^D. This is done by considering the welfare effects of increasing b_1 in case where $b_1^D = b(v_1)$ implies pooling. Next we show that no $b_1^D < b(v_1)$ is optimal. The intertemporal welfare given pooling in the first-period, denoted $W^P(b_1)$, and hence, the second-period optimal choice of the principal based on unchanged beliefs is given by:

19 Figure reproduced from Freixas, Guesnerie and Tirole (1985). P stands for pooling, SS for semi-separation and S for separation, and follow immediate from lemma 4.

$$W^P(b_1) = p \cdot S_H - \lambda \cdot (a + b_1 S_H) - \nu_1 \cdot C_L(S_H) - (1-\nu_1) \cdot C_H(S_H)$$

Now the following result is obtained:

Lemma 5: *For any* $b_1 \leq \frac{p}{1+\lambda}$*,* $W^P(b_1)$ *increases with* b_1 *if* $\frac{\partial x}{\partial S_\theta} = 0$ *(the non-resource case) For* $\frac{\partial x}{\partial S_\theta} < 0$ *and* $\frac{\partial C}{\partial x} = 0$ *(renewable resources with stock-independent costs)* $W^P(b_1)$ *still increases with* b_1 *. However, if* $\frac{\partial x}{\partial S_\theta} < 0$ *and* $\frac{\partial C}{\partial x} < 0$ *(renewable resources with stock-dependent costs), the sign of* $\frac{\partial W^P(b_1)}{\partial b_1}$ *is inconclusive.*

To show this result, we have that:

$$\frac{\partial W^P(b_1)}{\partial b_1} = p\frac{\partial S_H}{\partial b_1} - \lambda[\frac{\partial a}{\partial b_1} + b_1\frac{\partial S_H}{\partial b_1} + S_H] - \nu[\frac{\partial C_L}{\partial S_H}\frac{\partial S_H}{\partial b_1} + \frac{\partial C_L}{\partial x}\frac{\partial x}{\partial S_H}\frac{\partial S_H}{\partial b_1}]$$
$$-(1-\nu)[\frac{\partial C_H}{\partial S_H}\frac{\partial S_H}{\partial b_1} + \frac{\partial C_H}{\partial x}\frac{\partial x}{\partial S_H}\frac{\partial S_H}{\partial b_1}] =$$
$$[p - \lambda b_1 - \nu\frac{\partial C_L}{\partial S_H} - (1-\nu)\frac{\partial C_H}{\partial S_H}]\frac{\partial S_H}{\partial b_1} - [(\nu+\lambda)\frac{\partial C_H}{\partial x} + (1-\nu)\frac{\partial C_L}{\partial x}]\frac{\partial x}{\partial S_H}\frac{\partial S_H}{\partial b_1} - \lambda[\frac{\partial C_H}{\partial b_H} - b_1]\frac{\partial S_H}{\partial b_1}$$

As $\frac{\partial C_L}{\partial S_H} < \frac{\partial C_H}{\partial S_H} = b_1$, the first part is positive, as long as $b_1 \leq \frac{p}{1+\lambda}$. The third part is zero because of the first-order condition for the agent. In the standard case, $\frac{\partial x}{\partial S_\theta} = 0$ and, therefore, the second term is also zero. Therefore, $\frac{\partial W^P(b_1)}{\partial b_1} > 0$ in the standard case. For stock-independent renewable resources $\frac{\partial C}{\partial x} = 0$ and again the second term is zero. Therefore, it will also be the case that $\frac{\partial W^P(b_1)}{\partial b_1} > 0$ for these resources. However, for stock-dependent renewable resources ($\frac{\partial x}{\partial S_\theta} < 0$

and $\frac{\partial C}{\partial x} < 0$), the second term is negative implying that the sign of $\frac{\partial W^P(b_1)}{\partial b_1}$ is inconclusive. These results is summarised in Table 5.

Table 5: The value of $\frac{\partial W^P(b_1)}{\partial b_1}$

Type of resource	$\frac{\partial W^P(b_1)}{\partial b_1}$ is equal to
Standard case and case with renewable resources with stock-independent costs	$[(p - \lambda b_1 - v\frac{\partial C_L}{\partial S_H} - (1-v)\frac{\partial C_H}{\partial S_H}]\cdot\frac{\partial S_H}{\partial b_1}$
Renewable resources with stock dependent costs	$[(p - \lambda b_1 - v\frac{\partial C_L}{\partial S_H} - (1-v)\frac{\partial C_H}{\partial S_H}]\cdot\frac{\partial S_H}{\partial b_1} - [(v+\lambda)\frac{\partial C_H}{\partial x} + (1-v)\frac{\partial C_L}{\partial x}]\frac{\partial x}{S_H}\frac{\partial S_H}{\partial b_1}$

Table 5 shows that for stock-dependent cost renewable resources the sign of $\frac{\partial W^P(b_1)}{\partial b_1}$ cannot be determined because the first term is positive while the second term is negative. In the standard case and renewable resources with stock-dependent costs the value of $\frac{\partial W^P(b_1)}{\partial b_1}$ is positive. This result arises because the stock size does not enter the profit and welfare functions when $\frac{\partial C}{\partial x} = 0$. The reason for this is as follows. In a situation without a resource restriction (the standard case) where the continuation equilibrium implies pooling, the optimal dynamic first-period b_1 is optimally increased above the static optimal b_1^D. This happens because we know from lemma 1 that the principal induces the inefficient type to choose an inefficiently low level of harvest. However, if an efficient type pools with an inefficient type, the output of a low cost type will be inefficient as well. In order to mitigate this latter effect incentive must optimally be raised. The same conclusion applies to resources with stock-independent costs because profit and welfare are not affected by the stock size. However, for renewable resources with stock-dependent costs (hunting and groundwater) the resource constraint points in the other direction, since increasing b_1, increases the costs through its effect on the stock, and in case of pooling at $b(v_1)$ it is no longer clear that it is optimal to increase b_1 above $b(v_1)$.

From lemma 5 we cannot immediately decide whether it is possible to have $b_1^D < b_1(v_1)$ in a pooling equilibrium. It is, however, possible to show that this cannot be the case. In order to show this, consider a situation where we have that $b_1^D < b_1(v_1)$ and where this implies pooling. Let us analyse the effect on welfare when b_1 is increased. We decompose the effect on welfare into two parts. The first effect comes for increasing b_1, but for unchanged probability of revelation of the low cost type. Increasing b_1 increases the harvest for both types. Since the harvest for both types at $b_1^D < b_1(v_1)$ is smaller than in the static optimum, this clearly increases welfare. The second effect stems from changes in the probability of revelation due to increases in b_1. We know that Δb_1, the cost of concealment, is increasing in b_1. Moreover, we note that $\pi_2(v, L)$ only depends on b_1 through v. For any b_1 that implies pooling, the optimal second-period incentive scheme is the same, and for any b_1 that implies separation, the second-period is the optimal static incentive scheme. Therefore, the gain in period 2 is unaffected by b_1. From lemma 4 it follows that the probability of revelation increases due to increases in b_1. Furthermore, it is shown in Freixas, Guesnerie and Tirole (1985) that welfare is increasing in number of revealing firms.[20] Finally, we need to show that $b_1^D = b_1(v_1)$ if b_1^D induces a separating continuation equilibrium. However, the only reason why b_1 is optimally distorted from second best optimum ($b_1(v_1)$), is when there is a second-period gain in terms of better information, but since all information already is revealed at

20 For the firms that switch from pooling in the reference situation to revealing second-period social welfare is increased since the second-period scheme is now the full information scheme. For the pooling firms, the regulator can always duplicate his previous second-period incomplete information scheme in the reference situation (which is now sub-optimal) and leave social welfare unaffected.

$b_1(v_1)$ this is also an intertemporal optimal choice. These results are summarized in lemma 6.

Lemma 6: $b_1(v_1)$ is a lower bound on b_1^D.

In order to fully characterize how the inclusion of a resource constraint affects the contracting possibilities, we need to derive how the second-period gain from concealment is affected by changes in b_1. The second-period gain is given by:

$$\bar{\pi}(v) = a + b(v)S_L - C_L(S_{L,}x).$$

Inserting that $\pi^H(b(v)) = 0$ yields $\bar{\pi}(v) = b(v)S_L - b(v)S_H + C_H(S_{H,}x) - C_L(S_{L,}x)$. Differentiating with respect to *b(v)* gives:

$$\frac{\partial\bar{\pi}(v)}{\partial b(v)} = [S_L + b\frac{\partial S_L}{\partial b} - S_H - b\frac{\partial S_H}{\partial b}] + \frac{\partial C_H}{\partial S_H}\cdot\frac{\partial S_H}{\partial b} + \frac{\partial C_H}{\partial x}\cdot\frac{\partial x}{\partial S_H}\frac{\partial S_H}{\partial b} - \frac{\partial C_L}{\partial S_L}\cdot\frac{\partial S_L}{\partial b} - \frac{\partial C_L}{\partial x}\cdot\frac{\partial x}{\partial S_L}\cdot\frac{\partial S_L}{\partial b}$$

$$= [S_L + b\frac{\partial S_L}{\partial b} - S_H - b\frac{\partial S_H}{\partial b}] + b\cdot\frac{\partial S_H}{\partial b} + \frac{\partial C_H}{\partial x}\cdot\frac{\partial x}{\partial S_H}\frac{\partial S_H}{\partial b} - b\cdot\frac{\partial S_L}{\partial b} - \frac{\partial C_L}{\partial x}\cdot\frac{\partial x}{\partial S_L}\cdot\frac{\partial S_L}{\partial b}.$$

$$= [S_L - S_H] + [\frac{\partial C_H}{\partial x}\cdot\frac{\partial S_H}{\partial b} - \frac{\partial C_L}{\partial x}\cdot\frac{\partial S_L}{\partial b}]\frac{\partial x}{\partial S}.$$

For the standard case and renewable resources with stock-independent costs (timber cutting) $\frac{\partial\bar{\pi}(v)}{\partial b(v)} = [S_L - S_H] > 0$. However, for stock-dependent costs resources, we might end up in two situations because $\frac{\partial C_H}{\partial x}\cdot\frac{\partial S_H}{\partial b} \gtrless \frac{\partial C_L}{\partial x}\cdot\frac{\partial S_L}{\partial b}$. In one situation $\frac{\partial\bar{\pi}(v)}{\partial b(v)} > 0$ and in another situation $\frac{\partial\bar{\pi}(v)}{\partial b(v)} \le 0$. The situations are sketched in Lemma 7 and summarized in Table 6.

Lemma 7: For renewable resources with stock-dependent costs (hunting and groundwater) a sufficient condition for $\frac{\partial \overline{\pi}(v)}{\partial b(v)} > 0$ is that $\frac{\partial C_H}{\partial x} \cdot \frac{\partial S_H}{\partial b} \leq \frac{\partial C_L}{\partial x} \cdot \frac{\partial S_L}{\partial b}$.

However, $\frac{\partial \overline{\pi}(v)}{\partial b(v)} < 0$, if $[\frac{\partial C_H}{\partial x} \cdot \frac{\partial S_H}{\partial b} - \frac{\partial C_L}{\partial x} \cdot \frac{\partial S_L}{\partial b}] > -\frac{S_L - S_H}{\frac{\partial x}{\partial S}}$.

Table 6 shows that non-resources and resources with stock-independent costs the value of $\frac{\partial \overline{\pi}(v)}{\partial b(v)}$ is the same because $\frac{\partial C}{\partial x} = 0$ for the last case. The value of $\frac{\partial \overline{\pi}(v)}{\partial b(v)}$ may be lower or larger for resources with stock-dependent cost renewable resources because $\frac{\partial C_H}{\partial x} \cdot \frac{\partial S_H}{\partial b} \gtrless \frac{\partial C_L}{\partial x} \cdot \frac{\partial S_L}{\partial b}$.

Table 6: The value of $\frac{\delta \overline{\pi}(v)}{\partial b(v)}$

Type of Resource	$\frac{\delta \overline{\pi}(v)}{\partial b(v)}$ is equal to
Standard case and case with renewable resources with stock-independent costs	$[S_L - S_H]$
Renewable resources with stock-dependent costs	$[S_L - S_H] + [\frac{\partial C_H}{\partial x} \frac{\partial S_H}{\partial b} - (\frac{\partial C_L}{\partial x} \cdot \frac{\partial S_L}{\partial b})] \frac{\partial x}{\partial S}$

Given the resource constraint for stock-dependent cost renewable resources (hunting and groundwater), $b(v_1)$ is lowered. A smaller $b(v_1)$ implies, given lemma 3, that Δb_1 is smaller as well. Therefore, the cost of concealment is smaller. Moreover, from lemma 5, we know that if the two types pool at $b(v_1)$ in the dynamic setting, then the incentives of the principal to eliminate pooling via increasing b_1 are smaller. Since the gain from concealment can go both ways with respect to changes in b_1, we can identify two situations for forests and search fisheries.

Situation 1: $\frac{\partial \bar{\pi}(v)}{\partial b(v)} > 0$. Here second-period rent from pooling is smaller, and, hence, incentives to pool smaller, given that the principal sticks to $b(v_1)$ in period two as well. This situation is reproduced in Figure 3a, where S^{-RC} (S^{+RC}) indicates the set of b_1 that implies a separating continuation equilibrium in the non-resource case and the case of stock-independent cost resources (timber cutting). For a low cost agent in the case of renewable resources with stock-dependent costs (hunting and groundwater), second-period rent from pooling is smaller, but the cost of concealment is smaller as well. Therefore, nothing decisive about the effect of the resource constraint in these resources can be stated. In Figure 3a, we have presented a situation where the inclusion of a resource constraint does not alter to incentives to pool. However, if pooling would occur at $b(v_1)$, then the incentives for the principal to increase b_1 in order to separate the types are reduced.

Figure 3a: The situation, where $\frac{\partial \bar{\pi}(v)}{\partial b(v)} > 0$

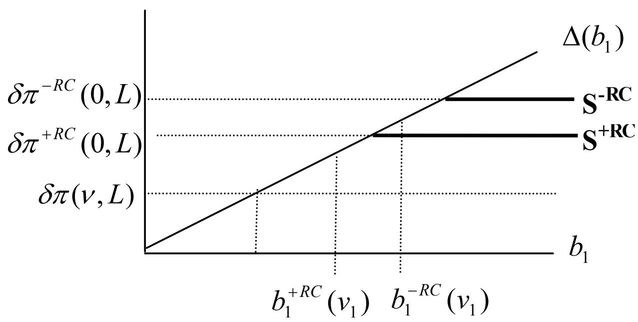
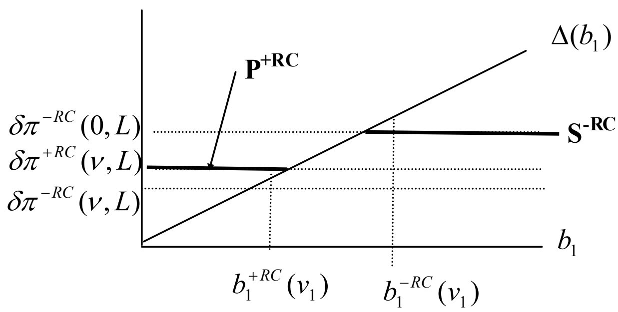


Figure 3b: The situation, where $\frac{\partial \bar{\pi}(v)}{\partial b(v)} \leq 0$



Situation 2: $\frac{\partial \bar{\pi}(v)}{\partial b(v)} \leq 0$. Here second-period rent from pooling is larger and the incentives to pool are larger, given that the principal sticks to $b(v_1)$. Together with the fact that smaller $b(v_1)$ implies that Δb_1 is smaller as well, undisputable increasing the incentives for a low cost type to pool.

Figure 3b shows an example where inclusion of a resource constraint for renewable resources with stock-dependent costs (hunting and groundwater) switches the incentives for the low cost type from separating to full pooling. Moreover, if types pool at $b(v_1)$ in the dynamic setting, then the principal's incentive to eliminate pooling via increasing b_1 is smaller.

These considerations can be summarized in the following way:

Proposition 2: The ratchet effect can either be enhanced or weakened by the presence of a resource constraint for stock-dependent cost resources

Finally, we can make some static comparative calculation of the effect of the resource constraint on the effect on the reduction in $b(v_1)$ in situation one (follows from (2)): $b(v_1)$ is smaller: 1) the larger $\frac{\partial x}{\partial S}$, and 2) the larger $\frac{\partial C_\theta}{\partial x}$ for renewable resources with stock-dependent costs (hunting and groundwater). Since a smaller $b(v_1)$, implies a smaller cost of concealment, this is to say that when $\frac{\partial x}{\partial S}$ and $\frac{\partial C_\theta}{\partial x}$ are large (large stock externality) , then $b(v_1)$ is reduced more and the cost of concealment is also smaller, in which case the likelihood of pooling at $b(v_1)$ is increased.

5. Conclusion

Laffont and Tirole (1993) show that if the principal could commit not to change the incentive contract in case of new information, it would be optimal to use a static second best contract in each period. As already noted in the introduction, long-run commitment is no option for most renewable resources, and, therefore, the effect of the ratchet effect cannot be avoided. In this case, the appropriateness of using these incentive schemes must be evaluated. Since the static second-best contract implies full separation, we can interpret the level of pooling as a measure for the inefficiency short-term contracting implies. More pooling implies more severe implication on welfare. This argument follows Milgrom and Roberts (1992) who show that to the extend that information lowers the variance with which second-period performance is measured (lowers the principals uncertainty about the type of the agent) information increases welfare. Since our results basically show that the level of pooling in a renewable resource contracting problem can be higher or lower, depending on parameter values and type of renewable problem at hand, the conclusion of our analysis is that the negative welfare effect of the ratchet effect might be more or less severe compared to situations without resource constraint.

However, we can still conclude that since the ratchet effect is prevailing in contracting for renewable resources, and that the presence of the ratchet effect might have serious consequences for the prospect of revealing information. Hence, if a main reason for applying information revealing mechanism is to reveal information, our result is bad news for this type of regulation. Jensen and Vestergaard (2002a) argue that the advantages of using an information revealing instrument in renewable resource contracting lay in the revelation of information itself. For many renewable resources cost data are not collected. For those resources where information on costs is collected the data are often based on statements by the extractors. If the extractor receives a subsidy on the basis of the stated costs and if the true cost type of the agent is unobservable, it is possible that the high cost agent pretends to be a low cost agent because it can increase its total subsidy by doing so. It must now be in the interest of the principal to design the tax mechanism such that the agents get an incentive to reveal the type correctly and, hence, incentive compatibility restrictions are included. Valuable information is, therefore, collected, but the price of collecting this information is that an information rent must be paid.

Regulation is complex and might lead to unexpected incentives. We have chosen to stick to a linear incentive scheme. The main reason for this is that it is the most realistic approach, since each agent will face the same contract. However, such a scheme is not without shortcomings (see Zou (1989)). Linear incentive schemes yield lower social value than piecewise linear schemes. By including non-linear incentive schemes, it is shown in Laffont and Tirole (1993) that the type of pooling which arises from linear incentive schemes can be eliminated. However, another type of incentives arises with non-linear schemes. If we use a non-linear incentive scheme, a dynamic interaction set-up can result in "take-the-money-and-run" behaviour. This is caused by the problem that in order to get an efficient type to reveal itself, one might use a high-powered incentive scheme, that this also attracts the inefficient type. In the second-period, the principal is now convinced that the agent is efficient, which causes an inefficient type to leave the industry. Such incentives might be especially severe in exploitation of renewable resources.

Since this paper is the first to deal with the presence of the ratchet effects in dynamic contracting for renewable resources under asymmetric information, our analysis points to the need for further research of the effect of the contracting instruments. In particular, it must be analysed how different instruments yield different incentive in a dynamic context and in this respect conclusions about the relative merits of different instruments must be reached. Such conclusions are arrived at in Jensen and Vestergaard (2002a), but only in a static context.

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